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ABLATIVE PERFORMANCE OF VARIOUS
LOW-DENSITY ELASTOMERIC COMPOSITES

by William E. Howell

Langley Research Center
Hampton, Va. 23365

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16. Abstract

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ABLATIVE PERFORMANCE OF VARIOUS LOW-DENSITY
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By William E. Howell
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SUMMARY

Results are presented of an experimental investigation of the performance of low-density (160 to 320 kg/m^3) silicone-phenolic and commercial ablative composites. Tests were conducted in air and in a mixture of 72 percent nitrogen and 28 percent carbon dioxide by mass. The ablative performance of the silicone-phenolic composites increased significantly as the density decreased. Also, the performance of these composites was found to be influenced by stream composition when tested at a cold-wall heating rate of about 0.2 MW/m^2, but the stream composition had little effect at a heating rate of about 0.6 MW/m^2. The addition of nylon to the silicone-phenolic material improved the ablative performance. Three commercial composites were tested and their ablative performances were compared with those of the silicone-phenolic composites of comparable densities. When the heat of degradation was considered, a commercial composite that incorporated a high volume percentage of ground cork filler appeared to be superior to the other composites. However, a comparison made on the basis of a more significant parameter, the ablative effectiveness, showed little difference in the ablative performance of the various composites.

INTRODUCTION

Ablative materials are used to protect spacecraft from the thermal environment encountered during atmospheric entry. Char-forming ablators have been found to be the most effective for a range of entry environments. Materials having a density of about 400 kg/m^3 can perform effectively at heating rates ranging from about 1.0 to 5.5 MW/m^2 (ref. 1); however, at lower heating rates and long exposures, the ablative performance of these materials is reduced because of their relatively high thermal conductivity. Recent work has shown the feasibility of fabricating low-density (160 to 320 kg/m^3) ablation materials, such as phenolic-nylon and silicone-phenolic composites, that perform effectively at low heating rates ranging from 0.1 to 0.7 MW/m^2. (See refs. 2, 3, and 4.)

An initial investigation of the ablative performance of low-density (160 to 320 kg/m^3) phenolic-nylon and silicone-phenolic composites is reported in reference 2. The

composites were tested at a cold-wall heating rate of 0.2 MW/m^2. The phenolic-nylon specimens were tested in air and the silicone-phenolic specimens were tested in a conceptual Martian atmosphere (72 percent nitrogen and 28 percent carbon dioxide). This investigation demonstrated the feasibility of fabricating effective low-density ablators. A comprehensive characterization of several commercial low-density composites is reported in reference 3. The study was directed toward a Mars lander application with cold-wall heating rates ranging from 0.068 to 0.68 MW/m^2 in air and in two mixtures of carbon dioxide and nitrogen. Reference 4 includes preliminary test results of several materials ranging in density from 160 to 750 kg/m^3 in air at cold-wall heating rates of 0.17 and 0.57 MW/m^2. For most of the tests reported, only back-surface temperature rises were presented. The investigation reported in reference 4 was also directed toward a Mars lander application.

The purpose of the present investigation was to evaluate and compare the ablative performance of 11 low-density (160 to 320 kg/m^3) composite ablation materials in low-pressure and low-heating-rate environments. Eight of the composite materials were developed at the Langley Research Center and will be referred to as silicone-phenolic composites. These eight composites were tested in air and in a mixture of 72 percent nitrogen and 28 percent carbon dioxide. The mixture of carbon dioxide and nitrogen is a conceptual Martian atmosphere and will be referred to in this paper as the CO_2 atmosphere. The other composite materials were the three most promising commercial materials reported in reference 4, which were tested only in air in the present study.

SYMBOLS

The physical quantities used in this paper are given in the International System of Units (SI). Factors relating the International System with other systems of units are given in reference 5.

E	ablative effectiveness, defined as qt/m where t is the time required for a specified back-surface temperature rise, J/kg
$\bar{E}$	ablative effectiveness based on the mass of material degraded, $Q/\rho x$, J/kg
Q	total convective heat input, J/m^2
q	cold-wall convective heating rate, W/m^2
t	time, s

m   mass per unit area of ablation material forward of the calorimeter, kg/m^2

x   thickness of pyrolyzed material, m

ρ density of uncharred ablation material, kg/m^3

SPECIMENS AND APPARATUS

The composition and density of the silicone-phenolic test specimens used in this study are shown in table I(a). They consisted of various percentages of silicone-elastomeric resin and hollow phenolic microspheres with 4 percent silica fibers. Two of the composites also contained nylon powder. A description of the processes used to fabricate the composites is available in reference 2. The only information obtained about the three commercial materials is given in table I(b).

Two different ablation-specimen geometries were tested in the present investigation. (See figs. 1 and 2.) The silicone-phenolic specimens were obtained by machining the fabricated composites into disks with a diameter of 7.6 cm and a thickness of 0.95 cm. (See fig. 1.) The three commercial composites were obtained from the manufacturers in the form of molded billets and machined into blunt-face specimens with a diameter of 5.0 cm. Specimens of the two silicone-phenolic composites containing nylon, MG 64 and MG 65, were also machined into this blunt-face configuration. A thermocouple was silver soldered to the back of a copper calorimeter that was bonded to the back of each ablation specimen. The calorimeter had a diameter of 0.95 cm and a thickness of 0.08 cm. A specimen holder was bonded to the back surface of each specimen with a room-temperature vulcanizing silicone rubber. This block served to isolate the calorimeter from the test environment, as well as to provide the means of attachment to the specimen inserter. Instrumentation of the blunt specimens (fig. 2) was similar to that of the flat-face specimens, except that the calorimeter was positioned so that the mass of ablation material per unit area (1.95 kg/m^2) in front of the calorimeter was the same for all specimens.

The tests were run in a supersonic arc tunnel designated apparatus B of the Langley entry structures facility. Reference 6 gives a detailed description of the arc system, and a schematic of the 5-MW test apparatus is contained in reference 7. For the present investigation the apparatus was equipped with a conical nozzle that had a throat diameter of 3.8 cm and an exit diameter of 15.2 cm.

TEST CONDITIONS

Flat-Face Specimens

The two nominal cold-wall heating rates for the flat-face ablation specimens were 0.22 and 0.57 MW/m^2. At each of these heating rates, specimens of each of the silicone-phenolic composites were tested in air and in the CO_2 atmosphere. Table II lists the test specimens and the corresponding test conditions.

Blunt-Face Specimens

The two nominal cold-wall heating rates for the blunt-face ablation specimens were 0.20 and 0.70 MW/m^2. Specimens of each of the commercial composites (A, B, and C) and the two silicone-phenolic composites containing nylon (MG 64 and MG 65) were tested in air at each heating rate. The test specimens and the corresponding test conditions are listed in table III.

TEST PROCEDURES

Prior to the testing of each of the specimens, the test apparatus was started and time was allowed for the test conditions to stabilize. A heating-rate measurement was obtained by using a thin-skin calorimeter and the specimen was then inserted with the front surface normal to the flow. The specimen was held in the test stream for a pre-determined exposure time to obtain a total heat load of 22.6 MJ/m^2, based on the measured cold-wall heating rate. (This heat load is representative of an out-of-orbit Martian entry.) During the specimen exposure, the output from the thermocouple attached to the copper calorimeter was recorded on digital tape. A second heating rate was measured as soon as the specimen was removed from the stream. The average of the two heating-rate measurements was used as the cold-wall heating rate for that test. The charred specimens were cross-sectioned, photographed, and measured to determine surface recession and char thickness.

RESULTS AND DISCUSSION

The objective of the present investigation was to determine the comparative ablative performance of 11 low-density (160 to 320 kg/m^3) composites. The parameter normally used for comparison of the ablative performance of materials (see, for example, ref. 1) is the ablative effectiveness E defined as

$$E = \frac{qt}{m}$$

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where q is the cold-wall convective heating rate, t is the time required for a specified back-surface temperature rise, and m is the mass per unit area of ablation material forward of the calorimeter. The effectiveness is the amount of heat accommodated at the surface per unit mass of material originally available. In order to use this parameter for comparisons, all specimens must be tested to the same back-surface temperature rise. Since back-surface temperature rise is of prime importance in spacecraft applications, E is a good measure of the ablative performance of materials. In the present investigation, however, the tests were run for the time required to give a total heat input of 22.6 MJ/m^2, and the back-surface temperature rises were considerably different for the different materials. Therefore, a different measure of ablative effectiveness $\overline{E}$ (refs. 1 and 2) was used. The parameter $\overline{E}$ is based on the mass of material degraded and will be called the heat of degradation. It is defined as

$$\overline{E} = \frac{Q}{\rho x}$$

where Q is the total convective heat input to a cold wall, x is the thickness of material pyrolized, and ρ is the density of the uncharred ablation material. Because of the difficulty in determining the exact location of the interface, the scatter in the data is greater for $\overline{E}$ than for E. Although $\overline{E}$ was used as the primary measure of ablative performance, a comparison of the blunt-face specimens was also made on the basis of E.

Flat-Face Specimens

The results of the arc-tunnel tests of the flat-face specimens are listed in table II. Table II(a) contains the results for a nominal cold-wall heating rate of 0.22 MW/m^2 and table II(b) contains the results for a nominal cold-wall heating rate of 0.57 MW/m^2.

Low-heating-rate environment.- The environment associated with the cold-wall heating rate of 0.22 MW/m^2 will be referred to as the low-heating-rate environment. The heat of degradation $\overline{E}$ of the seven silicone-phenolic composites (six without nylon and one containing nylon) tested in this environment is plotted as a function of density in figure 3. It is readily seen that when these composites were tested in air, the heat of degradation was only slightly increased by decreasing the density, whereas the specimens tested in CO_2 showed a significant increase in $\overline{E}$ with decreasing density. Also, $\overline{E}$ is higher in CO_2 than in air. This degradation of the ablative performance in air may be attributed to oxidation. If the carbon dioxide in the CO_2 test stream were completely dissociated into carbon monoxide and monatomic oxygen, there would be only approximately one-half as much oxygen available for oxidation as in air. Therefore, the specimens tested in air should have experienced more oxidation and, consequently, greater surface recession.

Figure 4 is a plot of surface recession as a function of density. It is evident that the specimens tested in air did experience greater recession than those tested in the CO_2 environment.

Density variations in the Langley-formulated composites were obtained by varying the percentage of phenolic microspheres. Although, as shown in figure 5, $\overline{E}$ is increased by increasing the percentage of microspheres (decreasing the density), char integrity is reduced for the lower density composites. Figures 6 and 7 show the char surface of the composites. The char strength deteriorates with increases in the percentage of microspheres. Composites with densities less than about 215 kg/m^3 produced chars so weak that they tended to spall in the test stream. The composites with densities greater than 215 kg/m^3 produced strong, hard chars with no evidence of spalling, although the higher density composites did develop broad cracks that extended in depth to the pyrolysis zone. These cracks diminished in width as the density decreased.

High-heating-rate environment.- The test environment associated with a cold-wall heating rate of 0.57 MW/m^2 will be referred to as the high-heating-rate environment. In this environment, the composites performed differently than in the low-heating-rate environment. As shown in figure 8, the heat of degradation increases with decreasing density, but the performance of the composites was not significantly affected by the test-stream composition. Surface recession is plotted as a function of density in figure 9. The data indicate that the test-stream composition had no significant influence on surface recession. Further study is required in order to understand the dominant surface-recession mechanisms associated with this test environment.

As shown in figure 10, $\overline{E}$ is increased by increasing the percentage of microspheres. Here, as in figures 8 and 9, the data indicate that the composites are relatively insensitive to the test-stream composition.

The chars of the composites are shown in figures 11 and 12 and appear very similar to those produced in the low-heating-rate environment. Composites with densities less than 215 kg/m^3 experienced spalling, whereas the higher density composites developed cracks. However, these cracks are considerably narrower than those produced in the low-heating-rate environment and the chars had a generally smoother surface.

The improved performance gained by the addition of nylon to the composites is shown in figures 3 and 8 for the low- and high-heating-rate environments, respectively. Nylon increases the specimen outgassing during heating and, therefore, reduces the convective heating. The char integrity of these specimens was good.

<center>Blunt-Face Specimens</center>

The results of the arc-tunnel tests of the blunt-face specimens in air are listed in table III. Table III(a) contains the results for a nominal cold-wall heating rate of

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0.20 MW/m^2 and table III(b) contains the results for a nominal cold-wall heating rate of 0.70 MW/m^2.

Low-heating-rate environment.- For the blunt-face specimens, the test environment with a nominal cold-wall heating rate of 0.20 MW/m^2 will be referred to as the low-heating-rate environment. The heat of degradation of the composites tested in this environment is plotted as a function of density in figure 13, together with the data for the flat-face silicone-phenolic composites tested in the low-heating-rate environment in air. One composite, MG 65, was tested in both specimen configurations and can be used for comparison. Composites A, MG 64, and MG 65 had higher $\overline{E}$ values than the silicone-phenolic composites, whereas the performance of composites B and C was approximately equal to that of the silicone-phenolic composites. The $\overline{E}$ value of composite A is approximately 30 percent greater than that of the silicone-phenolic composites of comparable density.

Figure 14 is a plot of surface recession as a function of density. The surface recession of the blunt-face composites was equal to or less than that of the silicone-phenolic flat-face composites. Two specimens of composite B and one specimen of composite A experienced the least amount of recession; of these three specimens, one had no measurable recession and the other two (one specimen each of composites A and B) experienced slight swelling.

All the blunt-face composites appeared to be shape stable and they retained relatively smooth, strong chars with no evidence of spalling (fig. 15). With one exception, composite C, they retained enough strength across the pyrolysis zone to hold the char. The char of composite C tended to fall off when the specimens were being removed from the test stream.

High-heating-rate environment.- The test environment with a nominal cold-wall heating rate of 0.70 MW/m^2 will be referred to as the high-heating-rate environment. The heat of degradation of the specimens tested in this environment is plotted as a function of density in figure 16. Here, as in the low-heating-rate environment, MG 65 was tested in flat-face and blunt configurations so that a comparison could be made between them. Composites A, MG 64, and MG 65 had higher $\overline{E}$ values than the silicone-phenolic composites used for comparison. Composites B and C had the lowest $\overline{E}$ values of any of the composites tested in this environment. Composite A had the highest $\overline{E}$ value, approximately 100 percent higher than that of the silicone-phenolic composites of comparable density. This seemingly high value of the heat of degradation may be misleading in terms of actual ablative performance and will be discussed further in the next section.

Surface recession is plotted as a function of density in figure 17. Composite A and one specimen of composite B experienced considerably less recession than any of the

other specimens. Composite B had the largest scatter in the data, with surface recession encompassing nearly the entire range of surface recession experienced by the other composites.

As shown in figure 18, the composites developed smooth, strong chars in the high-heating-rate environment with no evidence of spalling. Only one composite, C, developed a weak interface between the char and uncharred material and the char tended to fall off after testing.

Ablative Effectiveness

It was mentioned previously that ablative effectiveness E is the parameter normally used for comparing the thermal performance of ablative materials. Figure 19 is a plot of E as a function of density for the blunt-face specimens tested in the low-heating-rate environment. In these tests the lowest back-surface temperature rise (83 K) of any specimen at the end of heating was used to calculate E. It is readily apparent that composite A is not markedly superior to the other composites. The data for composite C overlap those for composite A, and although MG 64 and MG 65 show lower values of ablative effectiveness, this would be expected because of their higher density. Except for composite B, the composites performed similarly, considering the scatter in the data.

The ablative effectiveness of the blunt-face specimens tested in the high-heating-rate environment is plotted as a function of density in figure 20. Again, the lowest back-surface temperature rise (19 K) at the end of heating was used to calculate the ablative effectiveness. The trend is very similar to that for the low-heating rate environment; however, in the high-heating-rate environment, composite C actually has a higher effectiveness value than composite A, while MG 64 and MG 65 have values about equal to that of composite A. The ablative effectiveness of composite B is again less than that of the other composites.

It is clear from a comparison of figures 13 and 16 with figures 19 and 20 that the parameters E and $\overline{E}$ give different results. Since E is based on the back-surface temperature rise and this is of primary interest, then it should be the better parameter.

SUMMARY OF RESULTS

An investigation has been made of the ablative performance of eight composites developed at the Langley Research Center and three commercially developed composites ranging in density from 160 to 320 kg/m^3. These composites were tested at two cold-wall heating rates. Six of the Langley composites were tested in two different stream compositions (air and a mixture of 72 percent nitrogen and 28 percent carbon dioxide).

The other composites were tested only in air. The results of this investigation may be summarized as follows:

1. Silicone-phenolic composites with densities as low as 160 kg/m^3 performed efficiently at cold-wall heating rates of about 0.2 and 0.6 MW/m^2 in test streams of air and of a mixture of 72 percent nitrogen and 28 percent carbon dioxide.

2. The ablative performance of the materials improved significantly as their densities decreased. Char integrity was generally good down to densities of about 215 kg/m^3. Below this value, the char tended to spall during testing.

3. The ablative performance of the silicone-phenolic composites was influenced by the stream composition at cold-wall heating rates of about 0.2 MW/m^2, but it appeared to be independent of the stream composition at cold-wall heating rates of about 0.6 MW/m^2.

4. The ablative performance of the silicone-phenolic material was improved by the addition of nylon.

5. The heat of degradation of a commercial material containing a high volume percentage of ground cork was greater than that of the other composites tested at cold-wall heating rates of about 0.2 and 0.7 MW/m^2 in a test stream of air. However, when these materials were compared on the basis of ablative effectiveness, no material was significantly superior. Since ablative effectiveness is based on the primary design criterion, back-surface temperature rise, it is concluded that the ablative performance of the materials tested in this investigation is, in general, influenced primarily by their density rather than their composition.

Langley Research Center,
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TABLE I.- DESCRIPTION OF COMPOSITES

(a) Composites developed at Langley Research Center

| Composite | Nominal density, ρ, kg/m³ | Composition, percentage by mass | | | |
		Silicone	Phenolic microspheres	Silica fibers	Nylon powder
MG 33	315	50	46	4	---
MG 34	255	44	52	4	---
MG 35	255	33	63	4	---
MG 36	210	25	71	4	---
MG 45	175	18	78	4	---
MG 46	160	10	86	4	---
MG 64	315	25	56	4	15
MG 65	300	25	61	4	10

(b) Commercial composites

Composite	Nominal density, ρ, kg/m³	Company designation	Resin or binder	Fillers (a)
A[b]	240	SLA 561	Silicone	Cork, hollow microspheres, fibers
B[b]	235	SLA 220	Silicone	Hollow silica microspheres, fibers
C[c]	245	480-2	Silicone	Phenolic microspheres, fibers

[a]Materials listed are proprietary compositions. The fillers listed were determined from visual observation. The materials may contain other unknown ingredients.

[b]Supplied by Martin-Marietta Corporation, Denver Division, Denver, Colo.

[c]Supplied by AVCO Corporation, Space Systems Division, Research and Technology Laboratories, Lowell, Mass.

TABLE II.- TEST CONDITIONS AND RESULTS FOR

THE 7.6-CENTIMETER-DIAMETER

FLAT-FACE SPECIMENS

(a) $q \approx 0.22$ MW/m^2

[Total stream enthalpy, 4.0 MJ/kg; stagnation pressure, 0.04 atm (4.05 kN/m^2);
free-stream Mach number, 4.0; mass flow rate, 0.045 kg/s]

Specimen	Density, ρ, kg/m^3	q, MW/m^2	Char thickness, mm	Surface recession, mm	$\overline{E}$, MJ/kg
72% nitrogen and 28% carbon dioxide (by mass)					
MG 33 (1)	315	0.21	3.3	0.79	16.7
MG 34 (1)	255	.21	3.6	.91	18.1
MG 35 (1)	255	.20	3.6	.81	18.3
MG 36 (1)	215	.21	3.8	.99	20.6
MG 45 (1)	180	.24	4.6	.89	24.5
MG 46 (1)	155	.24	4.6	1.22	26.2
Air					
MG 33 (2)	315	0.22	4.3	0.84	13.4
MG 34 (2)	260	.21	4.6	1.42	13.8
MG 35 (2)	255	.22	4.8	1.09	14.5
MG 36 (2)	225	.21	5.3	1.22	14.5
MG 45 (2)	175	.21	5.8	1.35	16.5
MG 46 (2)	165	.21	2.5	5.69	15.6
MG 65 (1)	290	.23	3.8	1.00	16.4

(b) $q \approx 0.57$ MW/m^2

[Total stream enthalpy, 8.7 MJ/kg; stagnation pressure, 0.05 atm (5.07 kN/m^2);
free-stream Mach number, 3.5; mass flow rate, 0.045 kg/s]

Specimen	Density, ρ, kg/m^3	q, MW/m^2	Char thickness, mm	Surface recession, mm	$\overline{E}$, MJ/kg
72% nitrogen and 28% carbon dioxide (by mass)					
MG 33 (3)	310	0.53	3.8	0.79	14.8
MG 34 (3)	260	.52	4.1	.86	16.4
MG 35 (3)	265	.57	4.3	.86	16.5
MG 36 (3)	180	.57	5.3	1.40	19.0
MG 45 (3)	175	.56	5.1	1.19	20.6
MG 46 (3)	165	.57	5.1	1.30	21.3
Air					
MG 33 (4)	320	0.54	3.8	0.64	15.1
MG 34 (4)	245	.53	4.6	1.14	15.2
MG 35 (4)	255	.57	4.8	.89	16.1
MG 35 (5)	255	.64	4.8	.94	16.4
MG 36 (4)	215	.60	5.1	1.23	17.7
MG 45 (4)	175	.60	4.6	1.65	22.0
MG 65 (2)	285	.60	3.6	.80	19.3

TABLE III.- TEST CONDITIONS AND RESULTS FOR

THE 5-CENTIMETER-DIAMETER

BLUNT-FACE SPECIMENS

(a) $q \approx 0.20$ MW/m^2; air

[Total stream enthalpy, 3.0 MJ/kg; stagnation pressure, 0.02 atm   (2.03 kN/m^2); free-stream Mach number, 4.0; mass flow rate, 0.023 kg/s]

Specimen	Density, ρ, kg/m^3	q, MW/m^2	Char thickness, mm	Surface recession, mm	$\overline{E}$, MJ/kg	Temp. rise, K	E, MJ/kg
A (7)	240	0.19	3.6	[a]-3.3	23.8	83	8.6
A (8)	240	.21	3.3	.8	20.0		9.9
B (1)	235	.20	5.6	[a]-.3	14.6		5.3
B (2)	235	.19	5.8	.0	12.6		5.2
C (3)	245	.20	4.8	.8	13.4		8.0
C (4)	245	.21	4.8	.5	14.8		9.6
MG 64 (1)	320	.20	3.0	.8	15.1		6.8
MG 64 (2)	315	.20	3.0	.5	16.4		7.8
MG 65 (3)	300	.20	2.8	.8	17.1		7.9
MG 65 (4)	310	.20	3.3	.3	16.6	↓	7.1

[a]Negative recession indicates the material swelled.

(b) $q \approx 0.70$ MW/m^2; air

[Total stream enthalpy, 7.0 MJ/kg; stagnation pressure, 0.05 atm   (5.07 kN/m^2); free-stream Mach number, 3.7; mass flow rate, 0.045 kg/s]

Specimen	Density, ρ, kg/m^3	q, MW/m^2	Char thickness, mm	Surface recession, mm	$\overline{E}$, MJ/kg	Temp. rise, K	E, MJ/kg
A (9)	240	0.69	2.5	0.3	31.1	19	10.6
A (10)	240	.70	2.5	.3	31.6		9.0
B (3)	235	.70	5.1	1.3	14.1		6.5
B (4)	235	.69	5.1	.3	16.0		7.2
C(1)	245	.75	4.6	1.3	15.7		11.5
C (2)	245	.73	4.6	1.5	14.8		13.5
MG 64 (3)	310	.69	3.0	.8	17.4		9.6
MG 64 (4)	310	.72	3.3	.5	18.5		9.3
MG 65 (5)	310	.70	3.3	.8	16.8		9.0
MG 65 (6)	315	.69	3.3	.5	17.3	↓	8.9
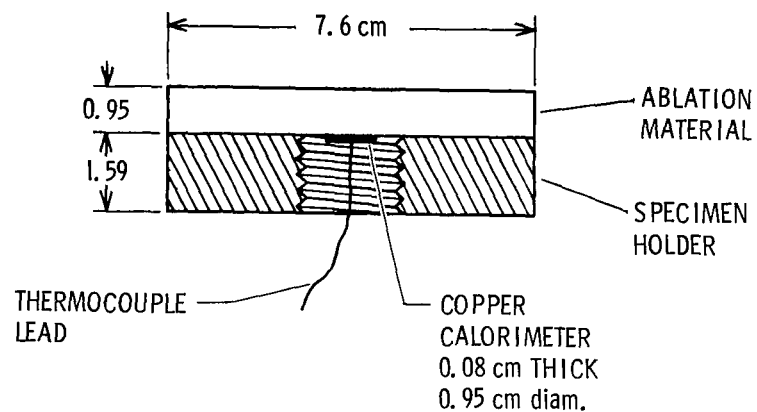
Figure 1.- Flat-face ablation-specimen configuration.
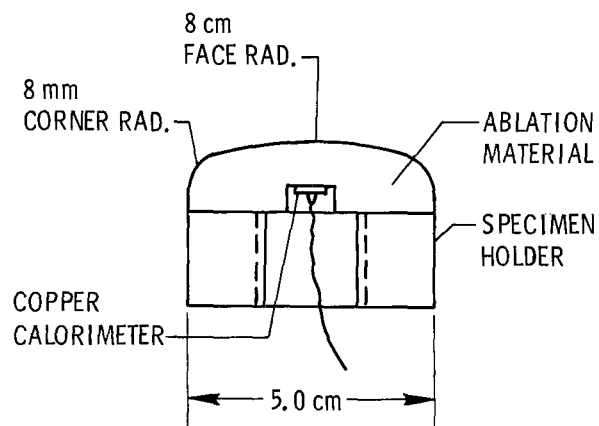

Figure 2.- Blunt-face ablation-specimen configuration.
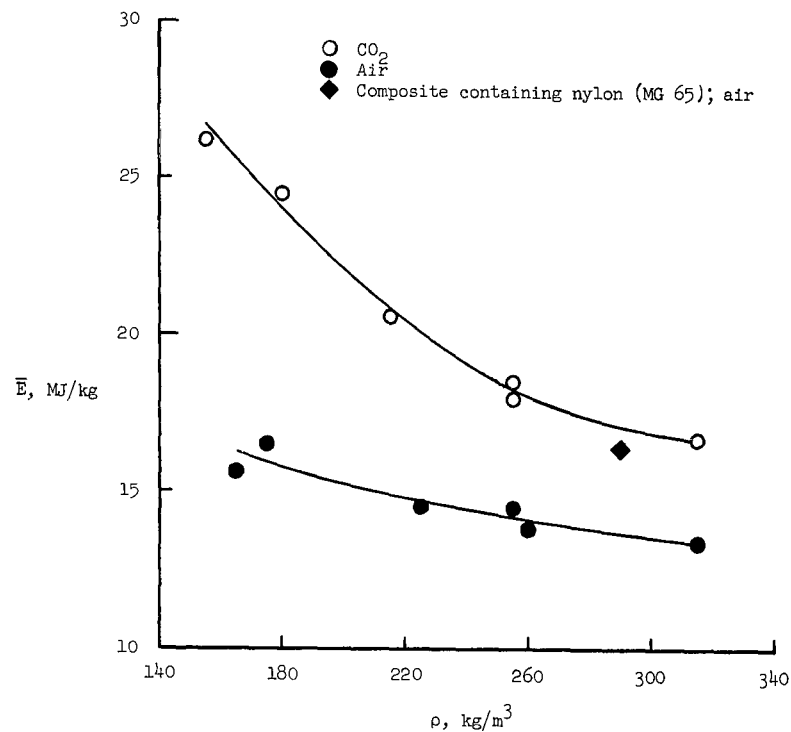
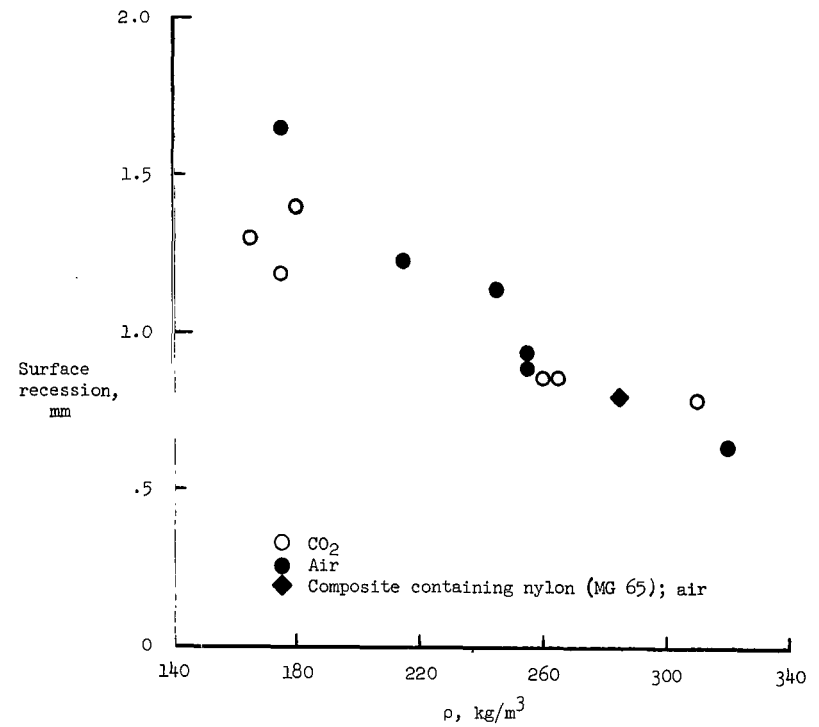Figure 3.- Effect of density on heat of degradation of silicone-phenolic composites tested at $q \approx 0.22$ MN/m^2.
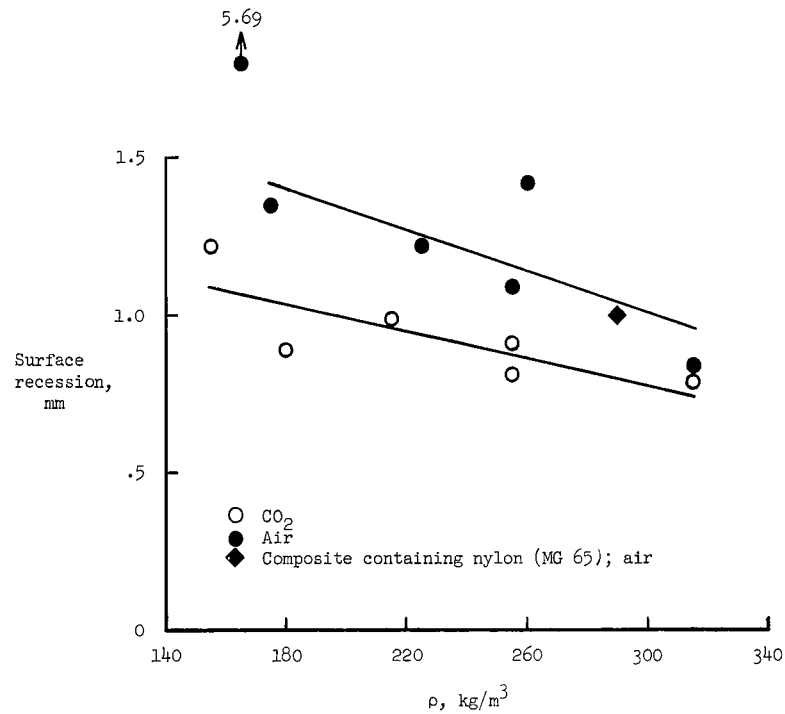
Figure 4.- Effect of density on surface recession of silicone-phenolic composites tested at $q \approx 0.22$ MW/m^2.
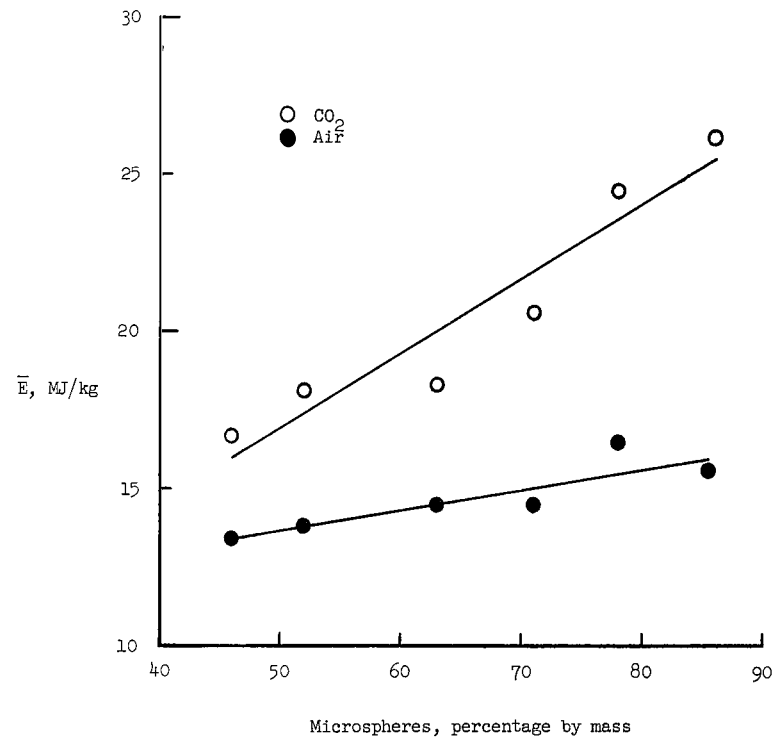
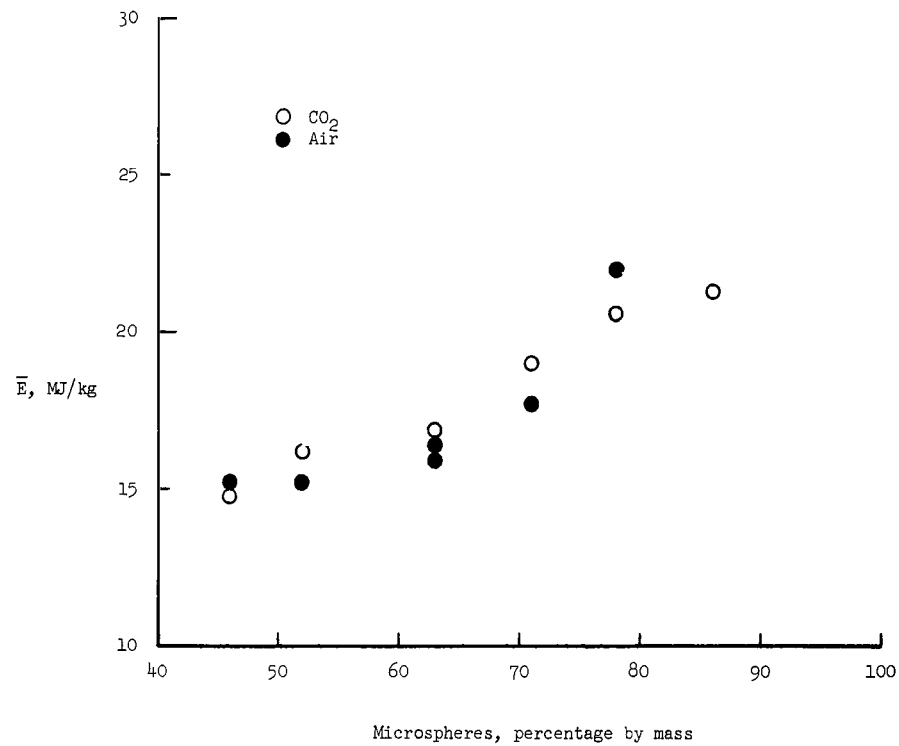Figure 5.- Effect of phenolic microsphere content on heat of degradation of silicone-phenolic composites tested at $q \approx 0.22$ MW/m^2.

MG 33 (1)

$\rho = 315$ kg/m^3
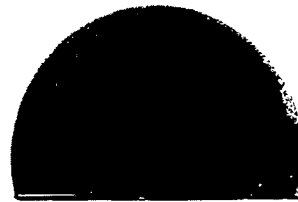
MG 34 (1)

$\rho = 255$ kg/m^3
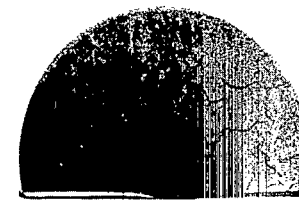
MG 35 (1)

$\rho = 255$ kg/m^3

MG 36 (1)

$\rho = 215$ kg/m^3

MG 45 (1)

$\rho = 180$ kg/m^3

MG 46 (1)

$\rho = 155$ kg/m^3

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Figure 6.- Surface and cross-sectional views of composites tested
in stream composed of 28 percent carbon dioxide and
72 percent nitrogen at $q \approx 0.22$ MW/m^2.

MG 33 (2)

$\rho = 315$ kg/m^3
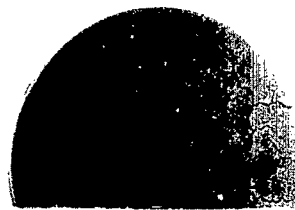
MG 34 (2)

$\rho = 260$ kg/m^3
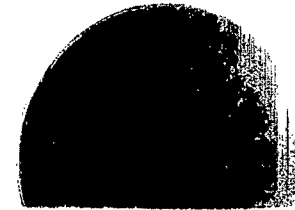
MG 35 (2)

$\rho = 255$ kg/m^3

MG 36 (2)

$\rho = 225$ kg/m^3

MG 45 (2)

$\rho = 175$ kg/m^3

MG 46 (2)

$\rho = 165$ kg/m^3

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Figure 7.- Surface and cross-sectional views of composites tested in air at $q \approx 0.22$ MW/m^2.
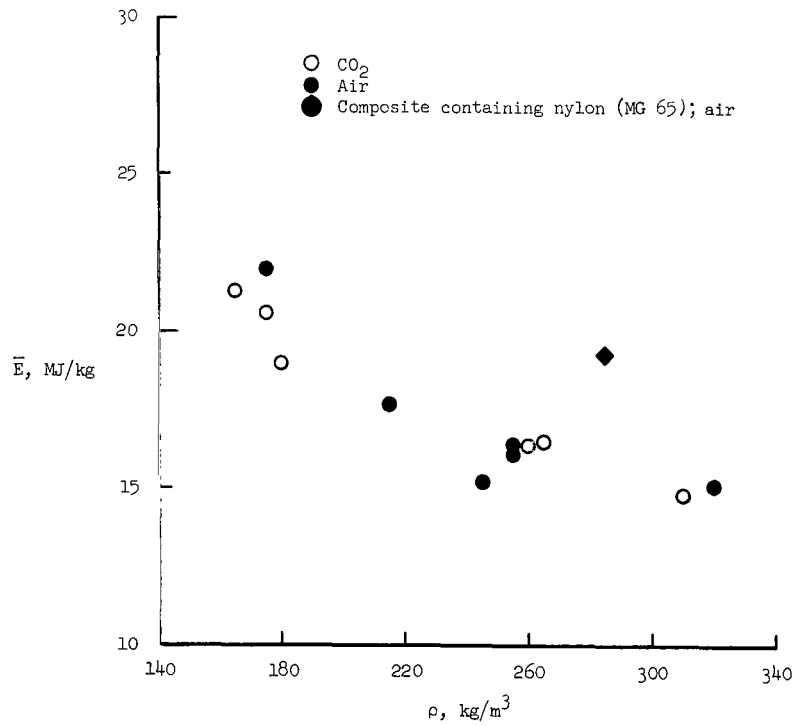
Figure 8.- Effect of density on heat of degradation
of silicone-phenolic composites tested at
$q \approx 0.57 \ MW/m^2$.

Figure 9.- Effect of density on surface recession
of silicone-phenolic composites tested at
$q \approx 0.57 \ MW/m^2$.

Figure 10.- Effect of phenolic microsphere content on heat
of degradation of silicone-phenolic composites tested
at $q \approx 0.57 \text{ MW/m}^2$.

MG 33 (3)

$\rho = 310 \text{ kg/m}^3$

MG 34 (3)

$\rho = 260 \text{ kg/m}^3$

MG 35 (3)

$\rho = 265 \text{ kg/m}^3$

MG 36 (3)

$\rho = 180 \text{ kg/m}^3$

MG 45 (3)

$\rho = 175 \text{ kg/m}^3$

MG 46 (3)

$\rho = 165 \text{ kg/m}^3$
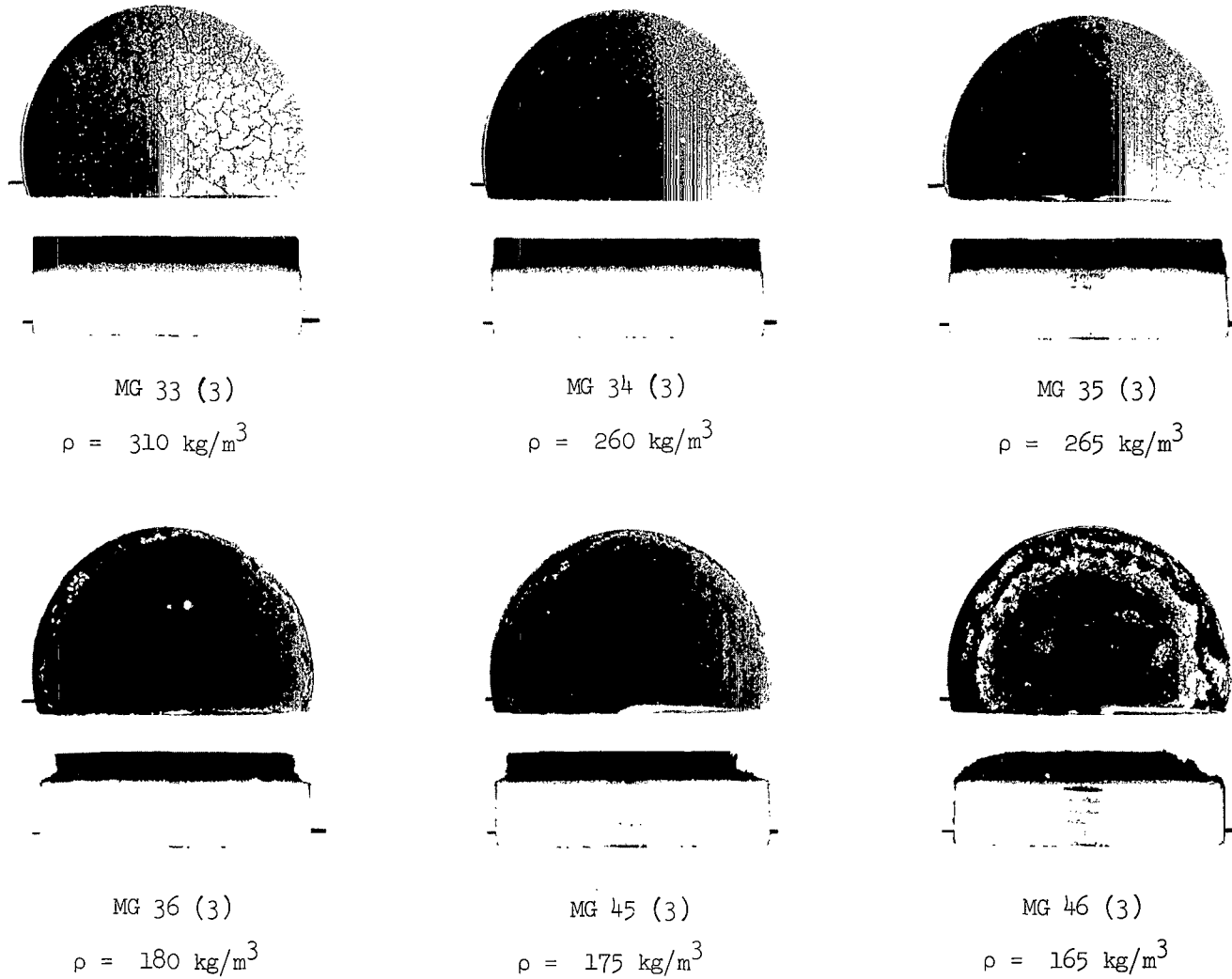
Figure 11.- Surface and cross-sectional views of composites tested
in stream composed of 28 percent carbon dioxide and
72 percent nitrogen at q ≈ 0.57 MW/m².
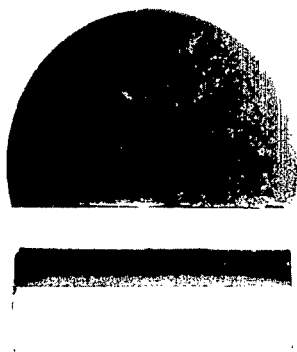
MG 33 (4)

$\rho = 320 \ \text{kg/m}^3$
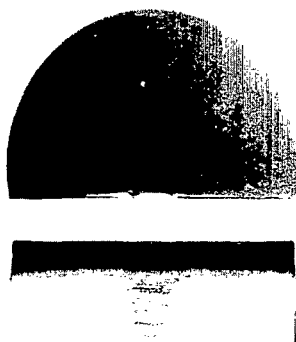
MG 34 (4)

$\rho = 245 \ \text{kg/m}^3$
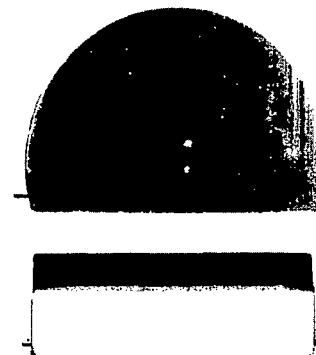
MG 35 (4)

$\rho = 255 \ \text{kg/m}^3$
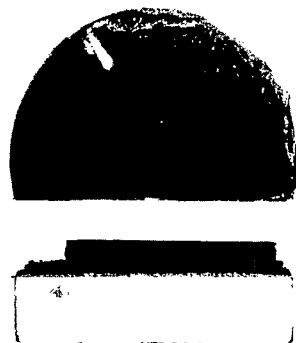
MG 36 (4)

$\rho = 215 \ \text{kg/m}^3$
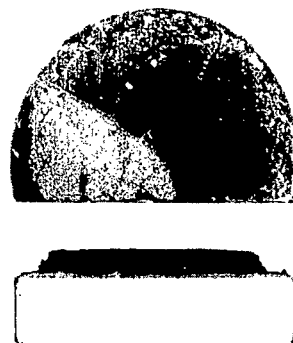
MG 45 (4)

$\rho = 175 \ \text{kg/m}^3$

Figure 12.- Surface and cross-sectional views of composites tested
in air at $q \approx 0.57 \ \text{MW/m}^2$.
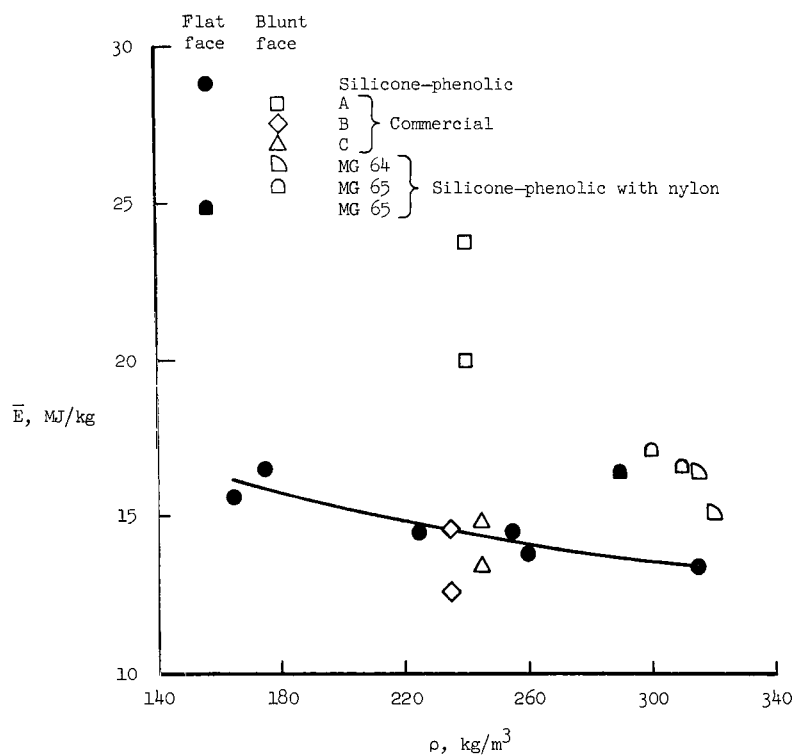
Figure 13.- Comparison of heat of degradation of commercial composites with that of silicone-phenolic composites tested in air at low heating rate.
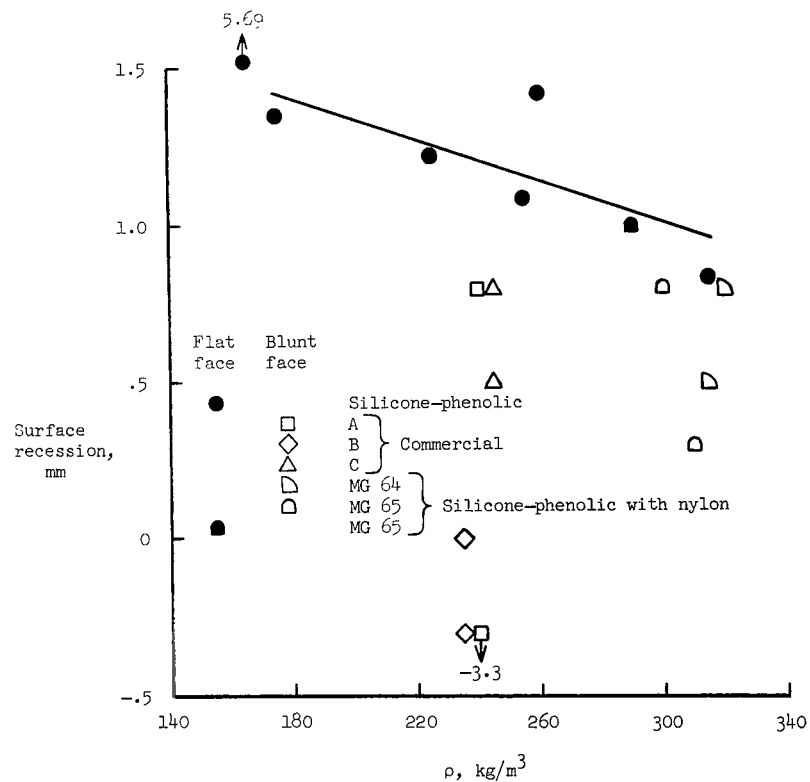

Figure 14.- Comparison of surface recession of commercial composites with that of silicone-phenolic composites tested in air at low heating rate.

A (8)

ρ = 240 kg/m^3

B (1)

ρ = 235 kg/m^3

C (3)

ρ = 245 kg/m^3

MG 64 (1)

ρ = 320 kg/m^3

MG 65 (4)

ρ = 310 kg/m^3
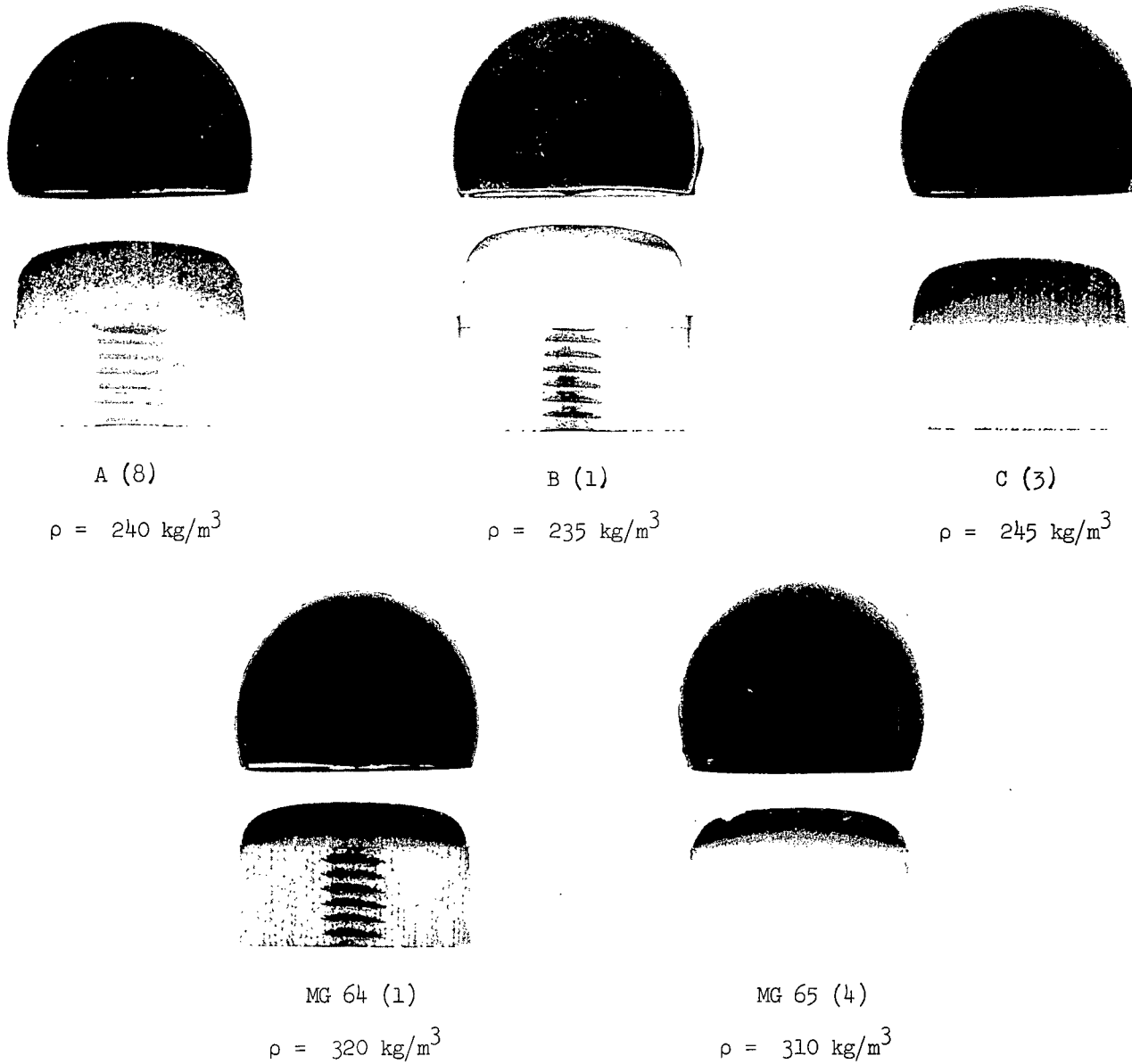
Figure 15.- Surface and cross-sectional views of blunt-face specimens
tested in air at $q \approx 0.20$ MW/m^2.
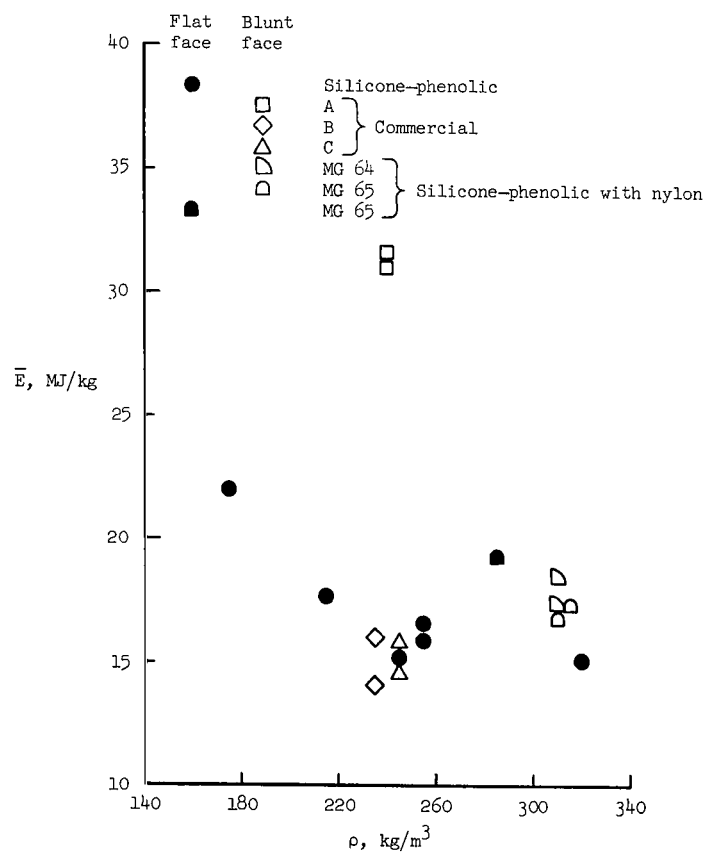
Figure 16.- Comparison of heat of degradation of commercial composites with that of silicone-phenolic composites tested in air at high heating rate.
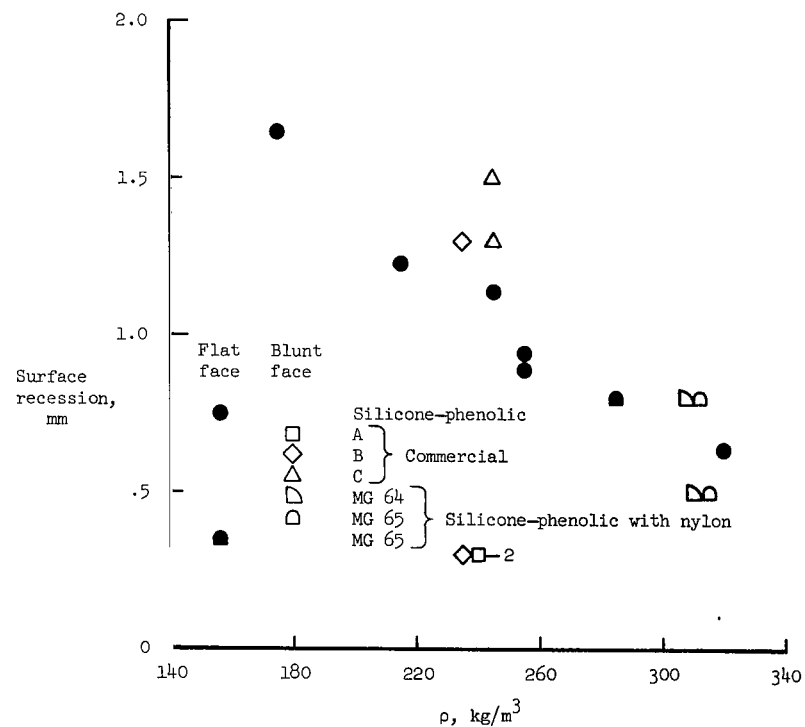
Figure 17.- Comparison of surface recession of commercial composites with that of silicone-phenolic composites tested in air at high heating rate.
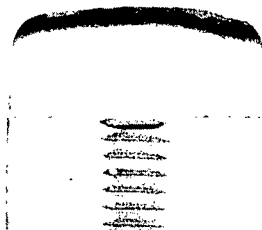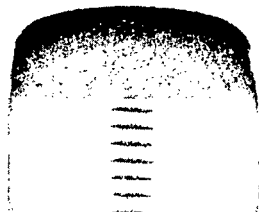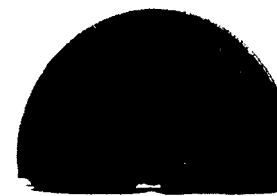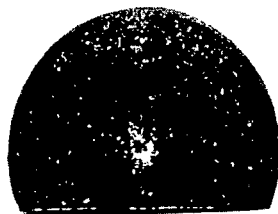
A (9)

$\rho = 240 \text{ kg/m}^3$

B (4)

$\rho = 235 \text{ kg/m}^3$

C (1)

$\rho = 245 \text{ kg/m}^3$
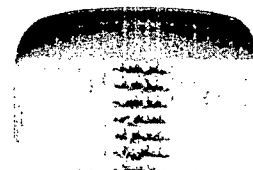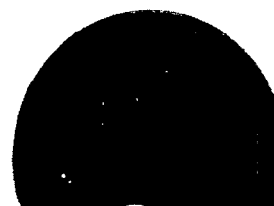
MG 64 (4)

$\rho = 310 \text{ kg/m}^3$

MG 65 (6)

$\rho = 315 \text{ kg/m}^3$

Figure 18.- Surface and cross-sectional views of blunt-face specimens
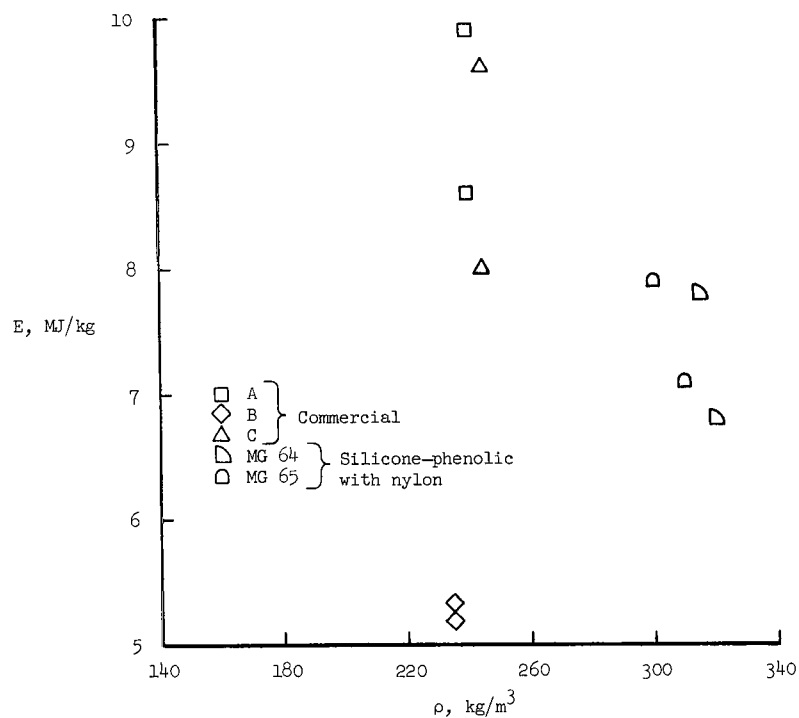tested in air at $q \approx 0.70 \text{ MW/m}^2$.

Figure 19.- Comparison of ablative effectiveness of blunt-face specimens tested at $q \approx 0.20 \text{ MW/m}^2$. Back-surface temperature rise, 83 K.
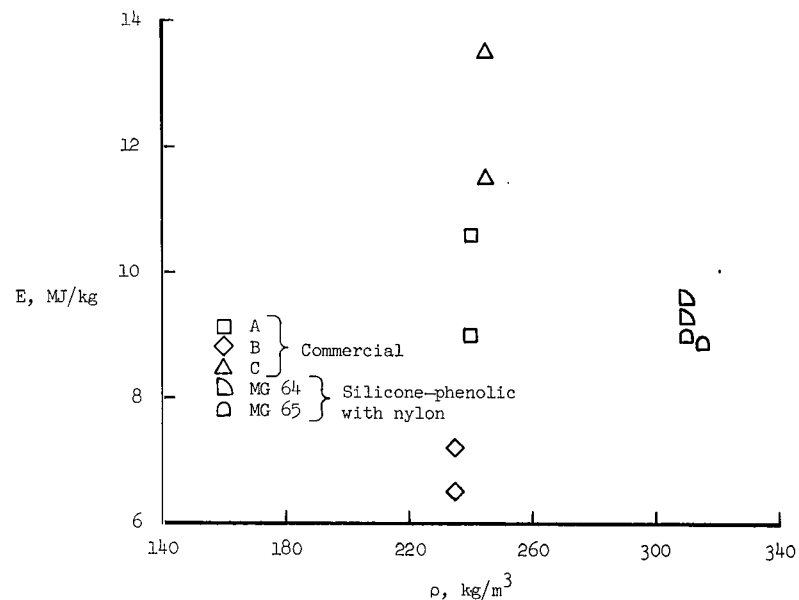
Figure 20.- Comparison of ablative effectiveness of blunt-face specimens tested at $q \approx 0.70 \text{ MW/m}^2$. Back-surface temperature rise, 19 K.

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— NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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